INFRARED SIGNATURES OF SHIPS AT SEA

by

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ABSTRACT

This thesis is a study in the infrared signature that a ship at sea will emit and how that signal can be used to improve the ability of the marine vehicle to detect and track targets. The need to develop marine infrared systems is established within the context of a brief comparison of the infrared detection scenario to the schemes presently in use. The virtues of exploiting the spectral characteristics of the infrared signature is demonstrated. Why the spectral system will have an improved range of detection or figure of merit when compared to imaging systems is discussed. Spectral lines and their expected signal strength for typical gas turbine operations are calculated. The types of target information that can be inferred from the spectral detection scenario is addressed. An expected submarine application is presented. Finally, the types of experiments needed to establish the parameters for the development of a full scale engineering model are proposed.

Thesis Supervisor: Mr. Juri Valge
Charles Stark Draper Laboratories

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INTRODUCTION

1.1 Advantages of an Infrared Navigational/Targeting Systems Onboard ships

If one stands in the flight pattern of an airport on a rainy foggy day, the roar of invisible jet airplanes is quite audible as they pass overhead. The aural senses detect the inherent sound output of the flying jet airplane. Through the centuries many technologies that exploit a target's characteristics or enhance the operator's natural abilities have been employed to improve the seaman's ability to detect and track targets; from ancient telescopes and bells to modern RADAR and SONAR systems. The inclusion of infrared sensor technology in this catalog of innovations will be but another step in the evolutionary process.

As will be demonstrated, infrared instruments are not replacements of current systems but rather adjuncts to the existing shipboard technologies. Modern information processing and computer technology has become sufficiently sophisticated so as to allow the infrared information to be displayed to an operator in real time and integrated with information from existing technologies. Infrared instrumentation technology promises to provide detector and optical systems that are economical and reliable.[1,2,3] Though the hardware

and software required to support the development of infrared systems is available, the impetus for the development of shipboard infrared systems is the exploitation of it's operational advantage over conventional technologies: the ability to passively detect and track targets at ranges longer than currently available during periods of low visibility.

This advantage is a direct result of the physics of the infrared signal's origin and propagation. The distinctive physical characteristic of the origin of the passive infrared signal is that the target signal or signature is an inherent property of the target vessel. The passive infrared target signal does not depend on a secondary source of energy. Common secondary sources of energy are reflected sunlight to provide for a visible and near infrared (.75 - 3 um) spectral response or the production of microwaves necessary for the operation of a RADAR system.

The propagation of the infrared signal also has a distinctive physical characteristic that contributes to the enhancement during periods of low visibility. Any radiant flux will be attenuated as it passes through the atmosphere. The transmission of the signal can be expressed[4]:

$$T = \exp(-(a + s)r) \qquad (1)$$

where:

T = transmittance

a = absorption coefficient

s = scattering coefficient

r = distance of travel of the signal

Though absorption can be important in some bands, scattering is generally the dominant effect if the traditional infrared transmission windows are employed. The scattering coefficient is the sum of the two basic kinds of scatter; small particle or Rayleigh scattering and large particle or Mie scattering[5]. Rayleigh scattering has a functionality of the fourth power of the inverse of the wavelength. There is essentially no Rayleigh scatter below about 1 um. Mie scatter has little dependence on wavelength and as long as the photon wavelength is small compared too the particle size it will be scattered indiscriminately. During periods of haze where the particulate or marine aerosol has dimensions of less than 0.5 um the dominant process will be Rayleigh scatter and the infrared signal will undergo low transmission losses when compared to the visible signal. During periods of fog with a peak size distribution of the marine aerosol between 5 - 15 um, Mie scattering is the dominant effect. Scattering losses affect the visible and infrared signals comparably. Hence until the onset of fog and rain the infrared

signal will have a decided transmission advantage over the visible signal in the marine atmosphere.

These physical characteristics of the infrared signal translate to improved passive detection and tracking ability with an infrared system during times of low visibility caused by adverse weather conditions or the loss of the secondary illuminating energy source such as the coming of night. In terms of navigation, a ship's ability to avoid collision or grounding will improve because targets can be detected at longer ranges. For the military vessel, periods of low visibility present the added liability of a limited capability to detect and track adversaries. These capabilities will be enhanced by the use of infrared systems and technologies.

1.2 Proposed Concepts

A comprehensive literature review reveals that there has been much interest in infrared systems and infrared signal processing. Infrared sensing is a technology that has been successfully applied to many varied applications; detection of energy loss in houses; U.S. Army night vision systems, sophisticated aircraft and satellite reconnaissance; and even at sea in Royal British Navy submarine periscopes and navigational systems. The large number of applications that have

occurred to date have centered on imaging technology.[6,7] The basis of the imaging scheme is to collect the sum total of the infrared energy originating from a defined field of view. The energy of the grey body target incident on the detecting element differs from the energy collected from the background on adjacent detector elements. The difference in the energy of the spatially collected signal is converted to an electronic signal, enhanced and displayed as a video on a television style screen. Detail of the target is provided by temperature and emissivity differences on the surface of the object when compared to adjacent regions of view. These systems rely on the total emitted energy difference between the target and background. They are quite successful and operational systems have been reported that can detect differences as low as several hundredths of a degree Kelvin. The imaging infrared sensor systems have developed sufficiently so that deployment onboard ship is feasible.

There is more and different information available in the infrared regime than has been exploited to date. In addition to the spacial information that is utilized by imaging systems, there is both temporal and spectral information available. Temporal, spectral and spacial system hardware and software requirements are generally not compatible and therefore each mode of information

can be treated separately.

It is the collection of spectral information that is investigated in this thesis. The extraction of this information requires that the infrared energy be spectrally collected over the spacial region of interest. A spectral approach to the processing of an infrared signal requires that a different approach be taken in the modeling and analysis of the target signal and that signal's propagation through the marine atmosphere. What will be demonstrated in this thesis is that the extraction of spectral information from the infrared signal will provide the user the ability to detect and classify targets at a higher figure of merit than is theoretically possible with imaging technology.

This task will be accomplished employing the following methodology. A brief description of the detection scheme in the infrared will be followed by a direct comparison to visible and Radar systems. This will demonstrate the concept that infrared technology can not be designed to replace but rather to augment the existing technologies. A discussion of the infrared signal and it's relationship to imaging technology will be compared to the spectral detection scenario. Again the goal is to demonstrate that the spectral technology is an adjunct to the imaging technology.

That the spectral concept is a viable and attainable technology will be demonstrated. The theoretical

modeling of the spectral system will be presented followed by supporting calculations. In conclusion experimental information that is required for a detailed engineering effort as well as a system that is envisioned for submarine installation is presented.

COMPARISON OF INFRARED TO EXISTING TECHNOLOGIES

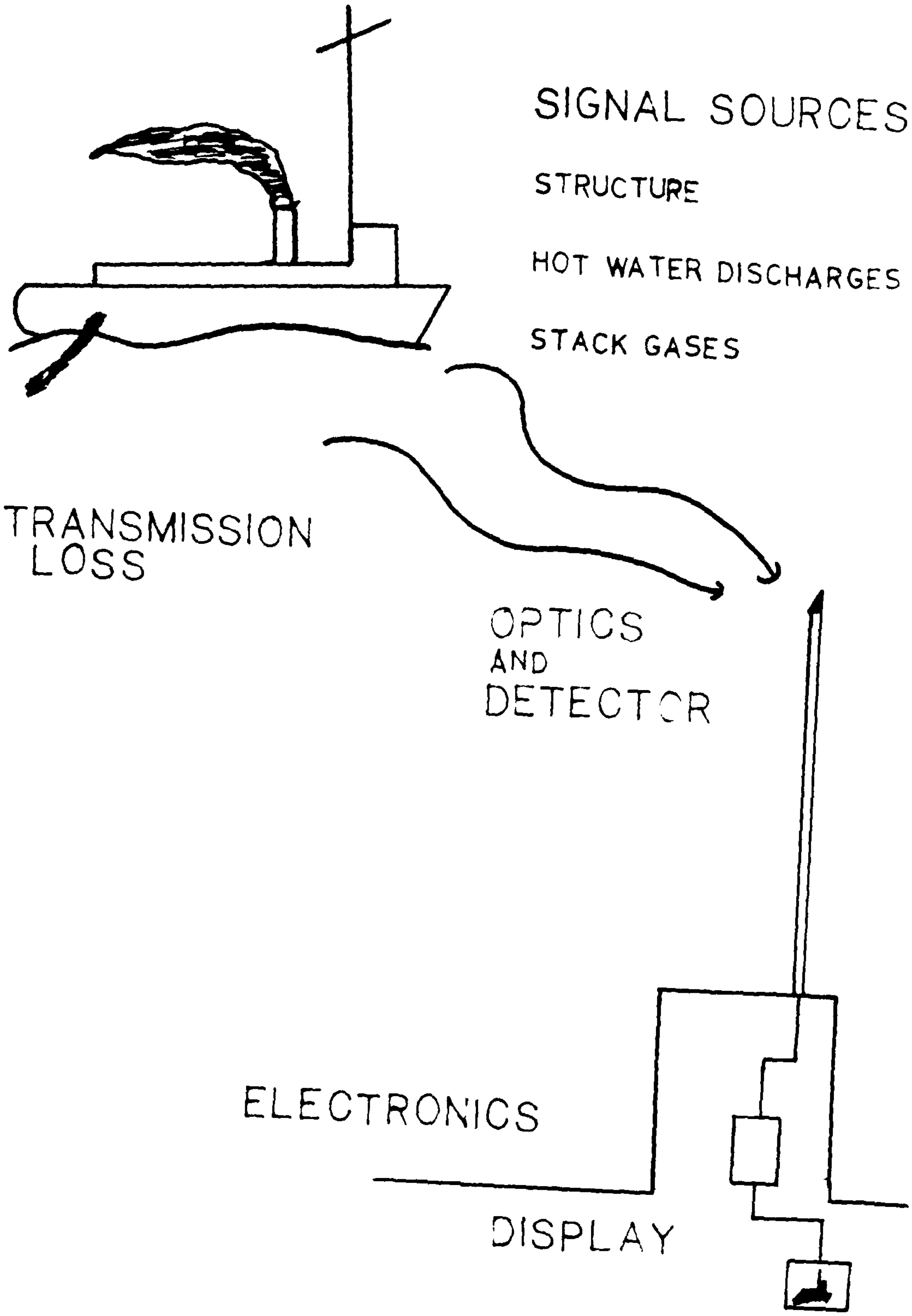
2.1 The Infrared Detection Scenario at Sea

Figure 1 depicts the scenario of the detection of a ship at sea through the use of an infrared sensing system. As is shown, there are four main elements required to produce a successful detect and tracking operation;

1. the strength of the signal the target produces
2. the loss of signal during the transmission
3. the optical system and detector
4. the electronics and displays

If any of the elements are missing or weak there will be degradation of the detection and tracking capabilities of this system. The thesis of this paper is that improvement in the detection and tracking capabilities of the currently conceived infrared systems can be made if the spectral qualities of the target signal are used. A general discussion of each of the elements follows so that the reader can appreciate how each area affects the integrated detection scenario. A detailed discussion of the source and the transmitting medium will be undertaken in the following chapters.

Figure 1. A schematic of the detection scenario at sea.



2.1.a The Source of the Signal

The source of the infrared signal is the ship's structure and the ship's activities. The ship structure is a gray body emitter. As such, the signature of the structure can be described in statistical thermodynamic terms that models the response of the target with respect to its environment. The actual radiant exitance of the ship's structure will depend only on the thermodynamic temperature of its surface and the emissivity of that surface. Factors that effect these parameters are:

1. the physical condition of the structural surface i. e. painted or rough
2. the meteorological conditions
3. the ocean conditions
4. the time of day and year

In general, anything that affects the equilibrium that exists between the ship's surface and the environment will affect the radiant exitance of the ship's structure. Attempts have been made to model the ship's surface. Reasonable success in these attempts has been reported.[8]

Ship activities also will produce signal in the infrared. The three most obvious sources of this signal are the hot water overboard discharges, the ship's wake and the hot stack gases. The hot water will radiate as

a point source on the side of the ship. A radiating trail of hot water will define the course of the ship until the water from the discharge is cooled to the ambient ocean temperature. The temperature increases in the water of the wake that are due to the action of the propeller also will form a warm water trail that will be more intense then the contrasting ocean.

The third major ship activity source of signal is the hot gases discharged through the stack. Some of these gases are spectral emitters. The chemical composition of the stack effluent is N_2, O_2, CO_2, CO, H_2O, unburned organic compounds, trace contaminate gases and particulate. All of these constituents are the products from the burning of fossil fuels. These gases exit the stack at between 300^{o}F and 400^{o}F. This temperature is sufficiently high so that excited vibrational states of these molecules will be significantly populated compared to populations found at the ambient conditions. For the portion of the stack effluent that is infrared active, the mechanism of relaxation of the excited vibrational states will be radiative decay as these molecules establish the equilibrium population levels of the ambient conditions. The radiation emitted by the molecules as they relax to ambient conditions will be characterized by discrete frequency photons that are particular to the radiating molecule.

2.1.b The Transmitting Medium

The atmosphere immediately above the ocean is the transmitting medium. The molecular N_2, O_2, H_2O, as well as the aerosols and particulates that are found in the marine atmosphere will interact with the infrared signal through absorption and scattering processes.[9,10,11] The medium has several identified "holes" that allow for transmission of infrared energy. Two regions of high transmittance are located between 2 and 5 microns and between 8 and 12 microns. Figure 2 is a schematic representation of how a target ship's signature will appear if a spectrograph were to be taken. As can be seen from Figure 2, the high transmission regions coincide with regions of emission for the grey body emitter as well as many of the spectral lines for the ro-vibrational decay of the stack gases.

2.1.c The Optical/Sensor System

This is the portion of the system that will see the infrared photons and convert them to an electrical signal for processing. It will consist of lenses and filters that transmit in the infrared while reducing the

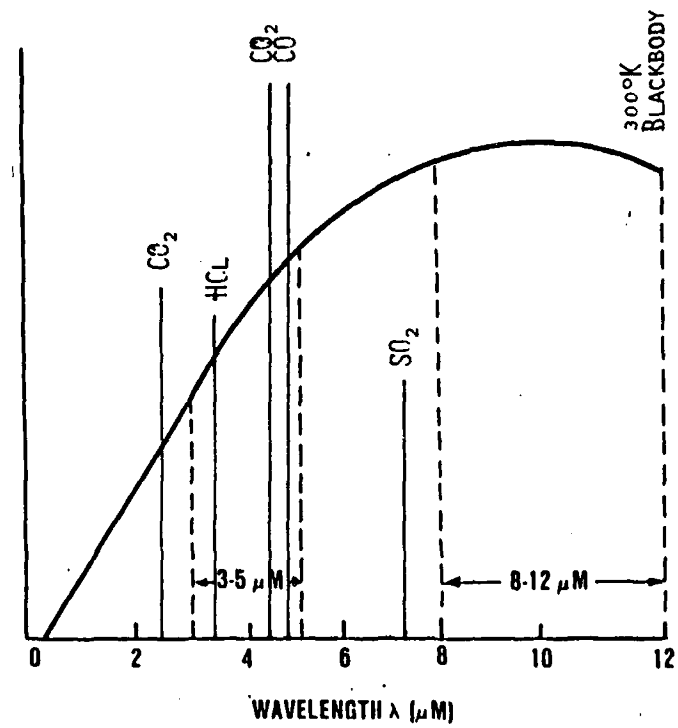


Figure 2. A schematic of the target emission lines. Note that this is a qualitative representation. The intensity of the lines is treated separately in chapter 4.

levels of non-infrared energy. Though systems exist that are capable of going to sea, numerous challenges still exist in this area for the development of a system that can fully implement the capabilities of infrared technology in an ocean environment.

The first significant hurdle is the lens material. It must be impervious to salt water erosion and

corrosion. The material or a material coating must also resist the growth of sea creatures. For military uses the material must withstand high levels of shock. High strength to resist large pressures is a requirement for submarine employment. It should be as non-wetting as possible so that it will shed water quickly to avoid obscuring the the infrared signal.

The cooling requirement of current detector technology also poses a problem for use in the shipboard environment. The high sensitivity, low noise detectors must be cooled to liquid nitrogen temperatures. A source of cooling such as liquid nitrogen or high pressure nitrogen tanks for Joule-Thompson coolers must be installed. Electronic cooling systems are being developed that may provide relief in this area. The cooling requirement will be difficult to meet on noise and space limited structures such as submarine periscopes.

2.1.d Electronic processing and display

Conditioning of the signal is performed to enhance the signal as well as to format information for the use of human operators. An imaging system will display the blackbody signal of the target in a manner that that the operator will recognize. The spectral option will entail a different type of signal processing. The

ro-vibrational lines of the spectral signature will form a series of lines that are present or absent. This signal will represent a series of yes-no responses that a computer can readily recognize. Further enhancements of the signal can be attained from ratios of lines or the recognition of trace elements.

2.2 Differences between the infrared and the visible or RADAR Scenarios

To understand how the infrared technology will be used to augment the current systems, a brief comparison of the major current technologies is in order.

The current visible spectrum detection system used on board ships is the human eye or a television styled system. The figure of merit of the visible system usually receives an assist from a magnifying element such as a pair of binoculars or a periscope. A ship, unlike an incandescent light bulb, does not act as a source of visible light. The ship at sea is a reflector of light from a secondary source. The sun or reflected sunlight from the moon are the primary source of visible light energy. A weak secondary source is the phosphorescence of the ocean. A direct consequence of the reflected light detection scenario is that when the source of reflected light is removed the target is no longer visible in this spectral region.

Visible spectral signals are also very susceptible to scatter by aerosols and particulate. Foggy and rainy weather reduce visibility not only by reducing the amount of radiation that is incident on the target but by the scatter of the signal after reflection as demonstrated by equation 1. Even sources of visible light, such as the headlights of a car, are difficult to see in foggy weather because of the scattering phenomena.

Radar systems use the microwave portion of the spectrum. The Radar signal is generated onboard the vessel and radiated outward. Though microwaves are more efficiently transmitted than visible photons, the best efficiency that can be obtained is as the square of the range for both the transmitted and the reflected signal. This requires that ship powering and cooling loads must be capable of driving the radar. Radar systems are non-passive by necessity and since large microwave sources are not found in nature they are consequently easily detected by an adversary. Modern technology ensures that counter-detection by the target will occur at distances far greater than the target can be detected by the emitting ship.

Infrared systems should be viewed as augmenting to the above current technologies: they will provide better passive detection during periods of low visibility. Visible systems will perform acceptably

during periods of good visibility. Radar systems will perform acceptably during periods of time when non-passive detection is an acceptable operational mode for the military vessel. The impetus for the development of infrared systems is to provide the mariner an integrated system that gives him the ability to detect and track targets at the horizon in all weather conditions.

COMPARISON OF THE SPECTRAL AND IMAGE SYSTEMS

3.1 The Ship's Signature

The infrared signature of a ship at sea will have three prominent features; the grey body emission of the ship's structure, the characteristic continuum of the hot water from the overboard discharges or the creation of wake and discrete spectral lines from the gases that compose the stack effluent. The imaging and the spectral detection scenarios handle the available information differently. Imaging systems collect the total amount of infrared energy emitted into the instantaneous field of view solid angle viewed by the detector element in its spectral bandwidth. A spectral system looks at the energy emitted as a function of frequency in the viewed solid angle. The signature of each feature will vary with both changing environmental conditions and ship controlled parameters such as speed, internal temperature and electrical load. Understanding the features of the infrared signature and relationship between those signatures and the detection methodology provides the basis for the design of infrared systems in the maritime environment.

3.1.a The Ship's Structure as a Grey Body Emitter

Black body radiation sources have been much studied.[12,13] The existence and theory of black body emitters is well described by studies in statistical thermodynamics and the heuristic arguments made by Planck at the turn of the twentieth century. Several properties of a black body radiator are critical to the development of the ideas of the ship's structure as an infrared emitter and are presented below.

1. The intensity of the radiation that a body emits is a function of the physical condition of its surface. If the surface is rough or coated the amount of radiation that is emitted from the surface will vary from the radiation that is emitted from perfect black body.
2. The intensity of the radiation that a body emits depends on the thermodynamic temperature of the surface of the object. If the object is in thermal contact with variable heat sources such as the wind and waves, the amount of radiation emitted by the body will vary as a function of its changing environment.
3. The description of the spectral intensity of the black body as given by Planck:[14]

$$W_{0\lambda} = 2\pi hc^2/\lambda^5 * [\exp(hc/\lambda kT)-1]^{-1} \quad (2)$$

where:

$W_{0\lambda}$ = spectral radiant emittance (erg/cm^2-cm^{-1})

h = Plank's Constant (6.63exp(-27) erg-sec)

λ = wavelength (cm)

k = Boltzmann's Constant (1.38exp(-17) erg/deg)

T = Thermodynamic temperature (^{o}K)

c = speed of light (2.99exp(+10) cm/sec)

This formulation of the black body emission must be reduced by the emissivity, ϵ , for the particular surface condition:[15]

$$W = \epsilon W_0 \qquad (3)$$

Figure 3 is a thermodynamic model of the ship's structure. As can be seen from the drawing there are numerous heat inputs and losses. An energy balance of these inputs and losses is required to describe the temperature of the element and hence its emissivity.

Figure 3 depicts a very complicated dynamic problem in heat transfer. This dynamic problem complicates the optical imaging problem because a surface at $32^{o}F$ radiates about 41% of the total energy radiated by a surface at $90^{o}F$ by the Stefan-Boltzmann relationship:[16]

$$E = \sigma T^4 \quad (4)$$

where:

E = total energy emitted (ergs/-cm^2-sec)

σ = Stefan-Boltzmann constant

(5.67exp(-14)erg/sec-cm^{2o}K^4)

T = Thermodynamic temperature (^{o}K^4)

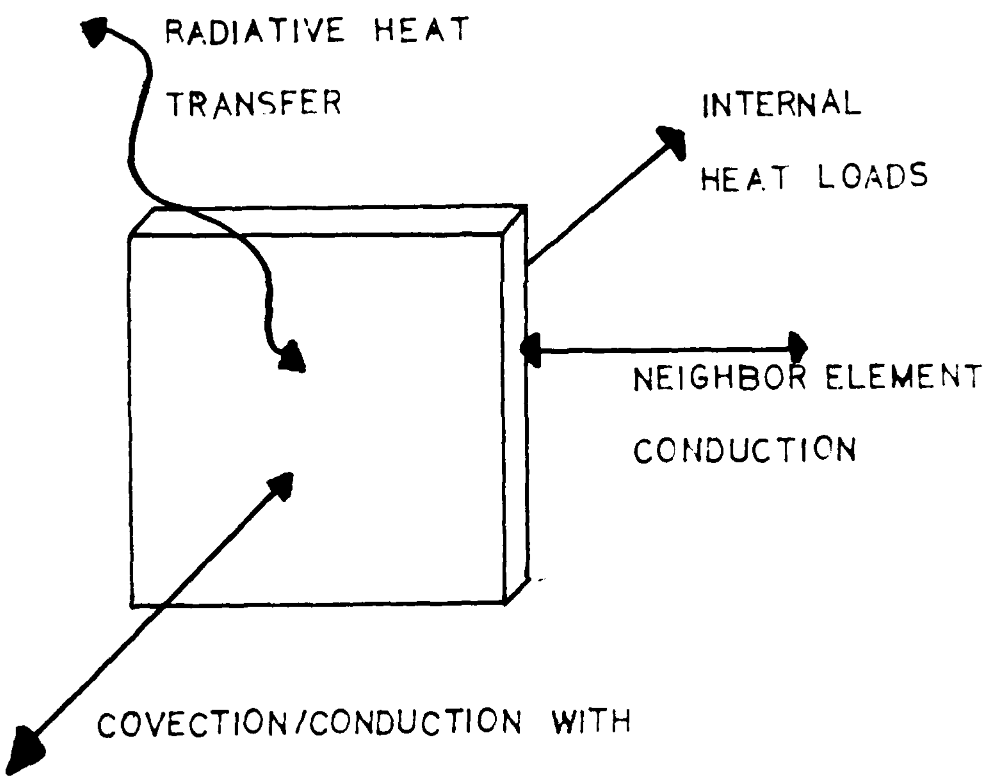


Figure 3. A differential element of the ship's structure showing the energy flows that affect the element.

3.1.b Hot Water Discharges and the Wake

The water that is pumped overboard will be around $150^{o}F$ - $175^{o}F$. The wake will be a few degrees warmer than ambient. The significant mechanisms that contribute to the cooling of the hot water discharge are:

1. convective and evaporative cooling by the wind
2. conductive and convective cooling by the ocean water
3. the emission of photons in radiative cooling

It is the radiative cooling mechanism that is sensed by the infrared system. As has been demonstrated the infrared signal will intensify and the normal features will broaden and lose there distinction with temperature. There will be no significant shifts in wavelength. The signal produced by the hot water in the overboard discharge is detectable only if viewed against the background of the lower temperature of the ocean. The detectability of the signal will last as long as a temperature difference exists between the discharge stream and the cool ocean water. Because of the rapid cooling of the discharged water and the oblique angle of view of the discharge stream or the wake these features of the ship's infrared signature are discounted as a

viable p t of the detection scenario.

3.1.c Stack Exit Gases

The exhaust gases from the combustion process exit the stack at a temperature of 300 °F - 400°F at a height of about 75 - 150 ft above the waterline. These gases exit the stack with a velocity dictated by the stack geometry, ship speed and fuel consumption. The stack effluent is immediately subjected to the forces of the wind. Cooling mechanisms for the stack gases are convective between the atmosphere and the stack stream, mixing between the stack stream and the atmosphere and radiative decay of the vibrationally excited molecules of the stack stream. It is the radiative decay process that provides the signal for detection by the infrared system.[16,17,18,19]

The chemical composition of the gases will be mainly N_2, O_2, H_2O, and CO_2. Varying amounts of SO_2, NO_2, CO, HCl and organic fragments will be present as minor constituents. The concentration of any of the minor constituents is a function of the engine operating parameters and the chemical composition of the oil that is being consumed. A significant population of the exit gases will be in excited ro-vibrational states when compared to the population distributions dictated by ambient atmospheric conditions. As the excited

ro-vibrational population distribution relaxes to the equilibrium distribution of the ambient thermodynamic temperature, molecules having allowed infrared transitions will radiate specific wavelength photons. Non infrared active species will decay from their excited states by collision with catalytic surfaces such as the ocean or the ship's structure and by the inelastic transfer of their energy to an infrared active molecule which will subsequently radiate the energy away. The large quantities of N_2 and O_2 that are infrared inactive have a high probability of channeling vibrational energy into molecules with infrared active states by the inelastic collision processes since there is a lack of surfaces available for collision with the stack effluent in the time frames of the vibrational relaxation process. The intensity of any of these lines can be estimated as will be demonstrated in chapter 4.

3.2 Background at Sea

Whether the detection scheme is imaging or spectral a knowledge of the background is essential. The background is the scene against which the object to be viewed must be contrasted. At sea this background, or radiance, will always consist of the ocean and the atmosphere immediately above the ocean. Both portions of the marine background are spectral emitters; they can

not be treated as black body radiators without the introduction of error.

At sea detection will occur at a 90° angle of elevation. At night the background radiance will reflect the Boltzmann population distribution of the infrared active states with high oscillator strengths. Because the atmosphere is at a low temperature only the low energy states of any molecule will be significantly populated and the night sky infrared radiance will fall off below 4 um. The daytime radiance is similar to the night sky with the addition of scattered sunlight below 3 um.[20]

The portion of the infrared radiance of the marine atmosphere above 4 um is dominated by the infrared activity of the CO_2 and the H_2O species. The radiance contributions of CO_2 are fairly well depicted by its infrared spectrum that is Lorentz broadened by collision with other atmospheric molecules. The contribution of H_2O infrared signal to the background is not as simple. H_2O contributes radiance to the marine atmosphere as a monomer as well as the higher molecular weight dimers, trimers and higher order polymers. This complication is a result of the strong hydrogen bonding exhibited by the H_2O molecule and is seen spectrally as a continuum. Condensed water; i.e. vapor or fog; adds a third dimension to the problem of background. Liquid H_2O is a very strong continuum absorber or emitter in the

infrared with prominent peaks for the O-H stretch at approximately 7.5 - 10 um.

The spectral system greatly benefits from the nature of the background radiance. First, the narrower the bandwidth employed the less background signal that will be collected. Since there will be lower noise a lower target signal can be tolerated without loss of detection range. A second benefit is that the infrared systems are primarily night systems. At night the natural background cuts off below 4 um. As will be discussed in chapter 4, most of the spectral target signal will also lie below 4 um and hence be in a region of low background during periods that the sun is not shining.

3.3 Transmission of the Signal

The infrared signal must be transmitted through the marine environment. Many models exist that attempt to describe this problem; the LOWTRAN computer simulation is one of those models.

The signal necessary to form an image must be the coherent focused signal directly from the target. The transmission losses to scatter and absorption in the marine atmosphere will be high.

The signal required for the spectral detection method need only be attributable to the target. Because of this modified requirement, the optical system can

collect energy over a much wider solid angle. Scattered photons of the sampled wavelength can contribute to the signal because they are directly attributable to the target. The increase in the flux due to the scattering of the signature photons can be calculated employing the LOWTRAN program radiance functions.[21]

3.4 Geometric Effects

A significant problem that occurs at sea is that the ability to detect objects at long ranges is limited by the physical horizon vice the visibility. This is depicted by Figure 4. As seen in Figure 4 the line of sight of an object of height h_1 with respect to the target of height h_2 can be calculated by geometric principles to be:

$$LOS = x_1 + x_2 \tag{5}$$

$$X_i^2 = ((R + h_i)^2 - R^2)^{1/2} \tag{6}$$

$$= 2Rh_i + h_i^2 \tag{7}$$

where:

LOS = line of sight (miles)

x_i = distance to the tangent of the earth (miles)

R = radius of the earth, 3963 (miles)

h_i = height of the object, (miles)

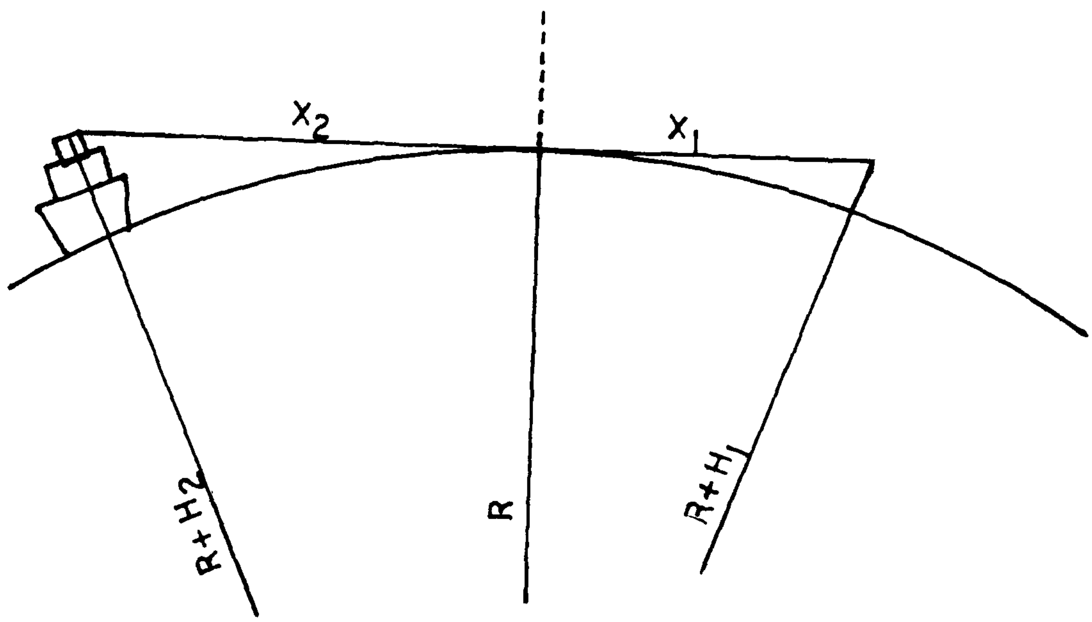


Figure 4. A depiction of the line off sight calculation.

Since R >> h_i the line of sight equation reduces to:

$$LOS = (2R(h_1^{1/2} + h_2^{1/2}))^{1/2} \qquad (8)$$

Upon converting the heights of the objects to feet the line of sight in miles can be calculated as:

$$LOS = 1.225\ (h_1^{1/2} + h_2^{1/2}) \qquad (9)$$

Thus a periscope at height h_1 of 6 feet will just see the top of a ship's structure with height h_2 of 100 feet at a distance of 15.25 miles.

For an image to be formed in the 8 -12 um region from the target ship structure, the target ship must present its structural area to the detector. As the ship sinks below the horizon and/or assumes a less than broadsides aspect, less and less of the ship structure will be visible to the observer. This phenomena occurs until the ship is completely over the horizon. As a result, the detected signal will decrease not only because of increasing distance but also because of the decreasing target area that is presented to the detector.

The signal due to the stack effluent is the highest point on the target ship and presents a fairly constant aspect to the detector. As will be discussed in section 4, the bulk of stack effluent signal lies in the 3 - 5 um region. Only when the ship structure is entirely below the horizon does the area that the stack gases present to the detector start to decrease. Because a

spectral system can operate on scattered signal, the fall off of the stack effluent target area over the horizon is not a limiting criteria. As a consequence the stack gases will be visible and identifiable to the spectral sensor at distances normally considered over the horizon.

3.5 Effects of the Environment

The principal reason to develop sensors and systems in the infrared portion of the spectrum is to improve detection and tracking ability in adverse environmental conditions. Either the imaging or the spectral systems will improve the current ability to perform this function. Understanding how the two infrared systems react to changing environmental conditions is essential to understanding the criteria for design or operation of either type system. The central elements that are required to understand how the environment affects the ability to detect in the infrared are:

1. Does the condition affect the strength or intensity of the target signal?
2. Does the condition affect the transmission of the signal through the marine environment? i. e. reduce the amount of energy that is incident on the detector
3. Does the condition increase the radiance of

the atmosphere or energy of the background?
i.e. lessen the contrast between the target
and the background

3.5.a Increases in the Wind, Wave Action and Rain

As a result of increases in the wind and wave action, the concentration of aerosols and particulate immediately above the ocean surface is increased. The increased concentration of aerosols and particulates will increase the amount of scattering of the target signal that will occur.[22] The increase in scattering will adversely influence the transmission of the imaging signal. Because the spectral system can be designed to use the scattered signal, the effects on the spectral system will be less severe; i. e. the scattering phenomena will tend to preserve the spectral signal. Rain will absorb as well as scatter the infrared signal. The net result will be a combination of the scattering and the molecular absorption effects on the transmission of the signal as shown by equation 1. The effects on the infrared signal by rain will be much more severe than the effects caused by aerosols and particulates.

The wind and wave action will increase the amount of convective and conductive cooling of the ship structure's surfaces. As the temperature of the surface decreases, the amount of energy in the 8 - 12 um band

will decrease according to the Stefan-Boltzmann relationship. Wave action and rain will wet the surface of the structure. This will cover the emitting ship's structure with a layer of water and tend to reduce the surface of the ship's structure visible to the detector. The radiation from the area for which water covers the surface will be characteristically more like water than structure. In a rain storm water displaces atmospheric gases as the background medium. The infrared signature of water is the background with which the target signal must be contrasted. Since the target structure signature starts to assume the characteristics of the water that is wetting its surface, the contrast of the target and hence its detectability will be reduced.

As will be demonstrated in chapter 4, most of the stack effluents signal will be emitted in the first 20 - 30 feet of travel after the gases leave the stack. Though some effect may occur, there is little time for the wind or the rain to interact with the constituents of the stack effluent prior to the emission of its radiative energy and the effects will be minor in nature. Since the signal will be very strongly spectral in nature, it will maintain its uniqueness with respect to the environment.

3.5.b Effect of Sunlight

Sunlight will heat the surface of the ship and enhance the target structural signal in the 8 -12 um region. The Stefan-Boltzmann law predicts that the total energy of the emitted signal will increase 36% if the ship's structural surfaces increase from $40^{O}F$ to $80^{O}F$. Sunlight will not affect the stack effluent signal in any discernable manner.

A day of strong sunlight will also increase the background signal or the radiance of the marine atmosphere in the 3 - 5 um range. This will be more detrimental to the spectral detection scenario that operates in this spectral region than an imaging scenario that operates in the 8 - 12um region.

DERIVATION AND CALCULATION OF THE STACK GAS EMISSIONS AS A SOURCE

4.1 Chemical Composition of the Plume

The stack plume is the effluent from the burning of fossil fuels. The plume can be fairly well defined given the chemical content of the fuel and the physical characterizations of the engine. For the purposes of this paper the General Electric LM-2500 turbine is used as an example.

For an unsaturated fossil fuel that has an average molecular weight of 144 grams/mole the stoichiometry will be approximately:[23]

$$C_{10}H_{24} + 15.5\ O_2 = 9\ CO_2 + 12\ H_2O + CO \qquad (10)$$

This relationship assumes that the fuel will not be combusted at 100% efficiency. Table 1 lists the fuel and air consumption rates for the listed LM-2500 parameters given as a typical mode of operation of this engine. From those consumption rates the chemical composition of the major constituents of the stack gases that enter the atmosphere can be determined.

Table 1. The consumption rates for an LM-2500 engine at the stated engine parameters.[24]

specific fuel ratio for 3600 RPM	.41 lbs/hr/HP
operating power	20000 HP
fuel to air ratio	1:50 by wt
Intake air composition	79% N_2
	20% O_2
	1% H_2O

fuel burned = 8200 lbs/hr or 2.59e+04 moles/hr

air burned = 410000 lbs/hr or 6.56e+06 moles/hr

Table 2. Stack emission concentrations of the principal constituents that result from the burn rates of Table 1.

Chemical compositions of stack gases

	from burn of fuel (mole/hr)	from the excess air (mole/hr)	totals (mole/hr)	(kg/hr)
CO_2	2.3e+05		2.3e+05	1.0e+04
CO	2.6e+04		2.6e+04	7.2e+02
H_2O	3.1e+05	6.6e+04	3.8e+05	6.8e+03
N_2		5.2e+06	5.2e+06	1.5e+05
O_2	-4.0e+05	1.2e+06	8.5e+05	2.7e+04
		TOTALS	6.7e+06	1.9e+05

The above calculations only deal with the major constituents of the effluent stream. Trace chemicals and particulates that result because of impurities in the fuel or small inefficiences in the combustion process will be present in the stack effluent at much reduced concentrations. Sulfur, nitrogen and chloride impurities in the fuel will burn and form the gaseous products SO_x, HCl, and NO_x.[23] Organic fragments resulting from the incomplete burning of the fuel will be present as well as particulate from the combustion process. All of the above will be present in the stack gases in small amounts that vary on the type of oil used and the operating conditions of the engine or boiler being monitored. Though present at small concentrations, the trace constituents will be important contributers to the infrared signature spectral scenario because of their high level of infrared activity and their uniqueness to the marine environment.

4.2 Sources of Infrared Activity

Though the chemical composition of the stack effluent is determined in section 4.1, there is no estimate of which of those molecules will radiate an infrared photon. This section will define that aspect of the problem. The problem of the intensity of the infrared signal will be taken up in section 4.3.

The process of vibrational relaxation by the emission of a photon has been extensively studied and characterized throughout the twentieth century. This study has resulted in several general rules that assist in the prediction of the signature of the gases that make up the chemical composition of the stack effluent. These rules are:[25]

1. The most probable vibrational transitions with the emission of a photon are those that have a change of one in the vibrational quantum number.
2. In order for a molecule to have an infrared spectra it must have a dipole moment that changes with respect to the normal coordinate of the vibration.
3. In order for a molecule to have a rotational spectra the molecule must have a permanent dipole.

The application of these rules will allow infrared spectral lines present in the stack effluent signature to be established.

4.2.a The N_2 and O_2 Signature[25]

N_2 and O_2 are two molecules that have neither a permanent dipole nor a dipole that changes in the direction of the normal coordinate. There is no

infrared spectral contributions from these molecules from unimolecular radiative decay. Large amounts of vibrational energy are stored in the vibrational modes of these two molecules since approximately 90% of the stack effluent by number is N_2 and O_2. How this stored energy affects the infrared signature is described in section 4.3.

4.2.b The CO Signature[25]

CO is a linear diatomic molecule that has both a permanent dipole and one the changes with respect to the normal coordinate and is therefore active in the infrared. The most prominent vibrational decay band head will be centered at 4.67 um. This line falls well within the 2 - 5 um transmission band. Since there is negligible CO that exists naturally in the marine environment and CO is a large percentage by number of the stack effluent, its spectral response will be an important portion of the stack effluent spectral signature.

4.2.c The CO_2 Signature[19]

CO_2 is a linear triatomic molecule that does not have a permanent dipole. Only the symmetric bend and the asymmetric stretch have normal coordinates with a

changing dipole moment and are thus infrared active with respect to the change of one vibrational quantum number rule. Other lines in the CO_2 spectrum that emanate from combination state transitions will be present but much weaker than the asymmetric stretch or bend transitions. Strong lines that will be centered at 14.99 um for the bend and 4.26 um for the stretch. Several moderate and weak intensity combination state transitions that will be activated in a 300 - 400 ^{o}F gas are shown in Table 3.

Table 3. Listing of several moderate and weak intensity lines of CO_2.

Transition	wavelength(um)
$20^{2}0 - 01^{1}0$	4.96
$12^{2}0 - 01^{1}0$	4.97
$110 - 000$	4.98
$003^{1} - 00^{0}0$	4.99
$04^{0}0 - 01^{1}0$	5.00
$00^{1}0 - 02^{0}0$	9.85
$00^{01} - 10^{0}0$	9.93

4.2.d The H_2O signatures[19]

H_2O is a tri-atomic molecule that is infrared active in all bands. There are several distinct features of the H_2O spectra that are results of the chemistry of the hydrogen bonding seen in this molecule. The H_2O molecule will form dimers, trimers and higher order polymers. These structures tend to smear the distinct spectra that is expected for a molecule and are responsible for the observed continuum. Water in the condensed phase is also present in the stack effluent and further complicates the spectra of water vapor. Both vapor and condensed phases of water are also major constituents of the marine atmosphere and will produce a background radiance rich in the characteristics of the water molecule. Because of the high levels of background and the lack of specificity in the spectra of H_2O, this molecule has little value in a detection scheme based on spectral response.

4.2.e The Trace Constituent Signature

SO_x, NO_x, HCl, HCN and organic fragments are all trace constituents that will be found in the stack effluent. They are all infrared active and will contribute spectral lines to the stack effluent signature that are very unique in the marine environment. The concentrations of these molecules will

be low in the stack effluent and consequently produce low intensity signals. Since these molecules are not found in the marine environment, band models used for transmission studies would predict little absorption of these signals during transmission and very low radiance levels at these frequencies in the marine environment. Thus the low intensity of the signals will be offset to some degree by the higher transmission and low background radiance at the frequencies of these spectral lines. The main band heads for these molecules are listed in Table 4.

Particulate that exists in the stack gases will radiate as a black body at the thermodynamic temperature of the surface.

Table 4. A listing of the major spectral lines for the trace constituents of the stack effluent.[17,18,23,25]

Molecule		Line (um)
HCl		3.34
HCN		14.1
		7.0
		3.0
-C-H-	Alkanes	3.5 and 7.4
	Alkenes	3.3 and 10-15
SO_2		19.3
		8.7
		7.3
NO		4.21
N_2O		7.78
		4.49

4.3 Intensities of the Infrared Signature

Section 4.2 established the qualitative infrared signature of stack gases. The task of predicting detectability requires not only the description of what

lines will be present but also an estimate of their intensity, the subject of section 4.3.

Two distinct geometric regions are of interest in the discussion of the intensity of the signal. The first region of interest is immediately above the stack itself. In this region the signal is described as being produced by the stimulated or spontaneous unimolecular radiative decay of excited vibrational states populated when the hot gases exit the stack itself. The second region extends several feet beyond the end of the stack. In this region it is proposed that the signal comes from the radiative decay of the infrared active states of molecules populated by the resonant energy transfer from the excited N_2 molecules that are present in the stack effluent. This analysis correlates observations of the stack effluent that have been reported by private communication.[26]

Qualitative observations of operating stacks both at sea and on land have been made employing imaging systems. It has been observed that a large infrared signal in the 2 - 5 um region is present. Spacially the 2 - 5 um signal extends 10 - 20 feet beyond the end of the stack. Very little signal in the 8 - 12 um region has been observed relative to the signal that is present in the 2 - 5 um region. What little signal that is observed in the 8 - 12 um region is confined to the area just above the stack.

4.3.a The Molecular Dynamics of the Stack Stream

The stack gas stream leaves the environment of the stack at a temperature between 300 - 400 ^{o}F. If this temperature is assumed to be a reasonable measure of the true statistical thermodynamic population distribution, then it can be inferred that population levels of all degrees of freedom will be inverted relative to the ambient marine atmosphere. Reasonable estimates of the inverted population distributions will be given by the Boltzmann distribution function:[27]

$$N(i)/N_0 = g * \exp(-(E(i)-E_0)/kT) \qquad (11)$$

where:

$N(i)$ = the population of i^{th} state

N_0 = the population of the ground state

g = degeneracy of the i^{th} state

$E(i)$ = Energy of the i^{th} state(erg)

E_0 = Energy of the ground state(erg)

T = Thermodynamic temperature(^{o}K)

k = Boltzmann constant(1.38exp(-16) erg/deg K)

Thus the number of molecules in the stream that are potential infrared emitters as the stack effluent cools can be calculated.

The cooling process of the vibrationally excited gases are described by two categories of mechanisms. The

first category of mechanism is the stimulated or spontaneous relaxation of the excited vibrational mode by the emission of radiation. The second category of mechanism is the channeling of the vibrational energy away from the molecule by collisional processes. These two mechanisms compete to relax the system and hence the rates of the respective mechanisms determine the intensity of the observed infrared signal.

The process of radiational decay produces the spectral infrared signature of the stack gases. This process has been the subject of much experimental work for the past 75 years. The kinetics of radiational decay, stimulated or spontaneous, is well characterized by by the Einstein A and B coefficients.[19] For the spontaneous radiative decay of vibrational states, the Einstein A coefficient would predict a decay time constant of about 10 - 50 msec. Therefore in a time of around 5 time constants, 50 - 250 msec, less than 1% of the original population of emitters will still be present. Using the mass flow rates of Table 2 and assuming that a stack exits to an ambient pressure of around 1 atmosphere through an exit area of 50 square feet, the exit velocity of the stack gases can be calculated to be on the order of 10 m/sec. The gases will traverse 1 - 2 feet for a strong (10 msec) line and 6 - 8 feet for a weak (50 msec) line during the time required to relax the population. These are

conservative distances since stimulated emission processes were not considered.

The above process competes with the removal of energy by collisional processes.

There is a limited range of outcomes that colliding molecules can undergo. Because the collisions involve molecules whose states are quantized the following tenet must not be violated: the colliding molecules must be in allowed states before and after the transfer of energy, therefore, only the quanta of energy that describes the difference between those two states can be transferred. The range of outcomes can be further limited by examining the first order wavefunctions of the states. Translational, rotatic , vibrational and electronic wavefunctions are generally treated as separable and therefore solution of the wavefunction of a molecule will give separate and distinct quantum numbers (eigenvalues) for translational, rotational, vibrational and electronic states. This fosters the concept that once energy is contained in a given mode it will tend to stay in that mode; i. e. the collision operator of the overlap integrals would have to couple a translational normal coordinate to a vibrational normal coordinate to have values not near zero for the transfer of energy from vibrational to rotational or translational modes.[28,29,30] The above concept defines the high probability inelastic transfer of

vibrational energy reactions as those with two molecules that have near resonant vibrational states or between a molecule and a surface.

In the region of the stream there are no surfaces readily available to the stack effluent. The only molecule that is near resonant to any of the radiators is the N_2 molecule. N_2, vibrationally excited to 2331.7 cm^{-1} is near resonant to the 2349 cm^{-1} asymmetric stretch of the CO_2 molecule. The statement of this reaction is:

$$N_2(v=1) + CO_2(000) = N_2(v=0) + CO_2(001) \quad (12)$$

Since N_2 has so much higher concentration than CO_2, the application of LeChatlier's principle would predict that the reaction would shift to the right. Driving this reaction to the right creates CO_2 in the excited 001 vibrational state and will increase the intensity of the 4.26 um CO_2 line.

As can be seen from the above discussion there are few physical processes in the stack effluent that will detract from the from the infrared signature. Reasonable estimates can be made of the strength of the signal based on the above concepts.

4.3.b Calculation of Population Levels and Signal Strengths

Assuming that the stack gases are in thermodynamic equilibrium upon exit from the stack, the equipartitioning of energy allows the population of the vibrational states to be calculated from the Boltzmann distribution as discussed above. The population of the ith state is found by dividing the desired ratio by the sum of the above ratios and multiplying by the total concentration found in Table 2. The results of the Boltzmann calculation appears in Table 5. The channeling of this vibrational energy into rotational or translational modes is predicted by quantum mechanics to be a low probability reaction the actual population that is calculated in Table 4. The mass flow rates calculated in Table 4 based on the Boltzmann ratios of Table 5 can be equated to the emission rate of photons due to the spontaneous radiative decay of the original population inversion if no competing mechanisms are present. A conservative estimate of the signal strength is presented in Table 6.

Table 5. Calculation of the expected populations for species found in stack emissions at temperatures of $300^{o}F$ and $400^{o}F$.

Gas	level	energy cm-1	T(F) =	N/NO $300^{o}F$	N/NO $400^{o}F$
H2O	000	0		1.00e+00	1.00e+00
	010	1595		4.35e-03	8.19e-03
	020	3190		1.89e-05	6.71e-05
	100	3657		3.85e-06	1.64e-05
	001	3756		2.75e-06	1.22e-05
			SUM	1.00e+00	1.01e+00
CO2	000	0		1.00e+00	1.00e+00
	010	667		1.03e-01	1.34e-01
	020	1334		1.06e-02	1.80e-02
	100	1342		1.03e-02	1.76e-02
	030	2001		1.09e-03	2.41e-03
	110	2009		1.06e-03	2.35e-03
	001	2349		3.33e-04	8.45e-04
	040	2668		1.12e-04	3.23e-04
	120	2676		1.09e-04	3.16e-04
	200	2684		1.06e-04	3.08e-04
	011	3016		3.43e-05	1.13e-04
	050	3335		1.16e-05	4.34e-05
	130	3343		1.12e-05	4.23e-05
	210	3351		1.09e-05	4.13e-05
			SUM	1.13e+00	1.18e+00

Table 5 continued.

Gas	level	energy cm-1		N/NO T(F) = 300^{o}F	N/NO 400^{o}F
CO	0	0		1.00e+00	1.00e+00
	1	2143		6.72e-04	1.57e-03
	2	4286		4.51e-07	2.47e-06
	3	6429		3.03e-10	3.88e-09
			SUM	1.00e+00	1.00e+00
N2	0	0		1.00e+00	1.00e+00
	1	2360		3.21e-04	8.19e-04
	2	4719		1.03e-07	6.70e-07
	3	7079		3.31e-11	5.49e-10
			SUM	1.00e+00	1.00e+00
O2	0	0		1.00e+00	1.00e+00
	1	1580		4.57e-03	8.56e-03
	2	3161		2.09e-05	7.33e-05
			SUM	1.00e+00	1.01e+00

Table 6. An estimation of the line strengths for the major spectral lines of the active states in the stack effluent.

Gas	rate photons/sec		wavelength	transition
T(F) =	300°F	400°F	um	
H_2O	2.68e+23	5.03e+23	6.27	010-000
	1.17e+21	4.12e+21	6.27	020-010
	2.38e+20	1.01e+21	2.73	100-000
	1.70e+20	7.49e+20	2.66	001-000
CO_2	3.52e+24	4.39e+24	14.99	001-000
	3.62e+23	5.88e+23	14.99	002-001
	3.72e+22	7.89e+22	4.99	003-000
	3.62e+22	7.70e+22	4.98	110-000
	1.14e+22	2.76e+22	4.26	001-000
	3.83e+21	1.06e+22	5.00	004-001
	3.73e+21	1.03e+22	4.97	120-010
	3.63e+21	1.01e+22	4.96	200-010
CO	2.92e+21	6.82e+21	4.67	1-0
	1.96e+18	1.07e+19	4.67	2-1
	1.32e+15	1.68e+16	4.67	3-2

4.3.c The 8 -12 um Signal of the Stack Effluent

The lack of signal in the 8 - 12um region is because there is no strong molecular radiator in that region as seen in Table 5. The only high concentration molecule that radiates in this region is the CO_2 bending vibration at 15 um, too high for an 8 -12 um detector to see. What signal that exists is the edge of the stack emitting as a grey body, particulate in the stack effluent emitting as a grey body and several weak lines as discussed in section 4.2 and shown in Table 4.

4.2.d The 2 - 5 um Signal Close to the Stack

The first portion of the observed signal in the 2 - 5 um region emanates from immediately above the stack. As demonstrated above there are no true competing mechanisms for the relaxation of the energy. Because of the time frames involved, this portion of the signal is the result of the relaxation by radiative decay of the inverted population levels of infrared active molecules that leave the stack.

4.2.e The 2 - 5 um Signal Away from the Stack

The distances calculated for radiational relaxation of the original population inversion do not explain the qualitatively observed length of the stack plume in the 2 - 5um image. Though the first order kinetic scheme for the emission is important for the first few feet above the stack it is clear that another process is activating the infrared signal in the downstream portions of the plume. The emission of photons by the infrared active molecules due to an inverted population does not explain the observed phenomena. The first place to look for an explanation would be the absorption and re-emission of the radiative energy by down stream molecules.

As the photons are emitted there will be some absorption in the stack stream. The highest concentration that will be seen are those prior to dilution and calculated in Table 2. For an apparent absorption coefficient of 19 $(\text{meter-atm})^{-1}$ the largest amount of radiation absorbed in a stack stream 15 meters long and at concentrations calculated in Table 2 will be about 3% from Beer's Law.[19] This percentage is not enough to account for the observed phenomena.

What can be noted from Table 5 is that there are large populations of N_2 molecules in excited states leaving the stack, 2.8e+23 molecules/sec. Large amounts

of energy are stored this molecule that is not infrared active. It is the redistribution of this large store of energy is the process that explains the qualitative observation associated with the 2 - 5um observations.

The N_2 molecules that leave the stack are thermodynamically at the same temperature as the infrared active gases. The inverted populations of these species must relax to the levels that are dictated by the ambient conditions. Since the transfer of energy between the rotational and translational modes is a low probability reaction, the energy of the excited N_2 molecules must be lost by an inelastic collision process with a surface that acts as a catalyst or with another molecule that has a resonant vibrational state.

As discussed, CO_2 has such a resonant state when compared to N_2. The first vibrational state of N_2 lies at 2331.7 cm^{-1}. The 001 state of CO_2 lies at 2349 cm^{-1}. These two states are resonant with respect to the transfer of vibrational energy. The stack effluent stream will be exposed to very little surface area during its first few feet of travel. The source of the strong 2 -5 um signal from the stack effluent can be postulated to be from the 4.26 um line of CO_2 due the 000 - 001 transition. The actual intensity of the line that is observed at sea will depend on a convoluted set of parameters. Any parameter that increases the amount of cool surface area that can catalytically react with

the stack effluent will reduce the intensity of the 4.26 um CO_2 line.

DEPLOYMENT OF THE SPECTRAL DETECTOR

5.1 Forms of Information Available in the Spectral Mode

As previously discussed, the information that is available for analysis in the spectral mode is a series of spectral lines of varying intensity. This information is extracted from the gross infrared signal through the use of filters, prisms or gratings. The element that is employed will depend on the geometry and the size as well as the level of sophistication of the detector system. The series of lines that is extracted by the detector system will provide information in two forms. The first form of the information is a series of yes/no-present/not present answers depending on whether or not the line has been detected: detection defined to be if the line intensity is above the background levels expected for the environmental conditions during the observation. The second form of the information will be the calculated ratios of the intensities of the detected spectral lines. The level of sophistication of both the detection system and the information desired will dictate:

1. the number of spectral lines required
2. the method of detection of those lines, i.e. whether gratings or filters are used

3. how well the background radiance must be established

5.2 Establishment of the Background Radiance

The radiance of the marine environment will have large changes depending on the weather and the time of day. The simplest way to establish the radiance would be through numerous averaged measurements stored in a computer and made available to the electronics of the system. This method would reduce the figure of merit of the overall system because its based on averages.

A methodology that calculated the radiance as the actual measurements were made would provide real time calibration of the system and remove much of averaged quality of the system. Since the shape of the radiance curve is fairly stable one measurement in an area that would be considered to have weak involvement with the perturbing influence, the target ship signature, should suffice to serve as a real time system calibration. The portion of the spectrum that should be used is around 2 - 3 um.

This wavelength region is suggested because there is insufficient energy in stack plume to activate the H_2O or CO_2 bands at that high of an energy. There will be a certain amount of activation of these bands by the sun and natural conditions. The radiance curve can be set

in real time and the figure of merit of the resulting detections improved.

5.3 Information Extracted from the Presence of Lines

The most basic spectral detector will observe one spectral line and the reference line as previously discussed. The presence of a target will be simply a yes or no based on the whether the spectral line is present or absent. The line chosen should have several characteristics in order that the figure of merit be as high as possible:

1. The line should be as unique as possible. Natural background levels of the line should be low. This will minimize any loss of intensity that will occur as well as make the line unique to its environment.
2. The line should be as intense in the stack effluent as possible.

If only one line were to be chosen, the 4.67 um line of CO would be an excellent choice as it meets both criteria. The 4.3 um line of CO_2 would rate as a strong second choice.

Though more sophisticated systems will use the information provided by more spectral lines, the above criteria for the selection of lines is still applicable. Some of the uses that could be designed into a system

that extracts more than one spectral line from the gross infrared signal are:

1. Increasing the figure of merit by using two or more lines to provide a higher probability detection scheme. The more lines that are employed, the fewer the number of false positives and negatives that will occur.
2. Finding lines that are unique to vehicles other than ships that are present in the marine environment will allow detection of that object. A jet engine has a much higher exhaust temperature than a ship and a small missile uses different fuel than is used in a ship. It should be possible to detect unique lines in the jet or missile exhaust. As an example, the N_2^+ species should be available in a jet exhaust. N_2^+ has prominent vibrational lines at 4.13um and at 4.53um as well as bands that will result from the recombination with the electron.[25] N_2H_4 rocket fuels should give rise to NH bands that can be found at 3.03um.[25]

5.4 Information Extracted from the Ratios of Detected Lines

Once the spectral lines are used to determine the

presence of a target vessel the ratios of the intensities of those lines can be used to extract information about the target itself. One use of the intensity ratios would be to confirm a detect. If the ratio of the CO to the CO_2 lines are found to be different than the ratios found in the environment, the probability of a true detect will be very high. Information unique to the target can also be ascertained by using the ratios of detected spectral lines. Some of these uses are:

1. As the speed of a vessel varies the efficiency of the engines will change and the ratio of the CO/CO_2 lines will vary accordingly
2. Different fuels from different parts of the world contain different concentrations of contaminates. This will result in different intensity ratios for the compounds of sulfur and chloride that are observed.
3. Different fuels will have different ratios of C^{12} to C^{14}. This will result in different ratios between the $C^{12}O$ and $C^{14}O$ lines that are detected.

Trade offs between the level of sophistication of the information that is desired and the sensitivity of the detector system that can be achieved in the limited geometries and harsh marine environment are important in

the very early stages of design of a spectral system.

5.5 The Spectral System as a Threat Warning Sensor

The two most obvious advantages of a spectral response system are its ability to improve detection ranges and the accuracy with which it can be operated. A third virtue is available, speed. From a military viewpoint, speed is an essential element of any detection system. In its simplest form the speed of a spectral system will be on the order of the microsecond sampling time of its detector. If only the presence of a few lines is used the need for sophisticated information processing is eliminated. Coupling the speed characteristics with the high figure of merit of this type system, a spectral system is ideally suited for threat warning functions.

CONCLUSIONS

6.1 Attributes of a Spectral Detection System

Throughout this thesis the theme has been maintained that there is no one type of system that will solve all detection problems. Radar, Sonar and visible spectrum systems should all certainly have their respective place in the design of a sensor suit. The inclusion of infrared sensors, both imaging and spectral, simply adds another dimension to the sensor suit. It is the designers job to integrate all these sensors into an efficient working package that is sensitive to the needs and tactics of the vessel on which it will be deployed.

The desirable attribute that infrared spectral detection systems bring to the detector suit is that they allow detection of targets in the marine environment at greater distances than are currently available during periods of low visibility. This advantage arises because of several physical characteristics:

1. The spectral stack effluent signal for the detection of target ships is relatively intense.
2. If a sufficiently narrow band width is selected then the amount of background that will compete with the signal will be minimized.
3. The band that is selected can be a very unique

characteristic of the perturbing influence such as the 4.67 um lines of CO when fossil fuels are burned or the 3.03 um line of the N-H band that should be present when hydrazine based fuels are burned.

A spectral systems will have many advantages in speed and simplicity of signal and information processing. If designed as staring type systems they will have the maintenance advantage of no moving parts. Today there are neither commercially available marine spectral systems in existence nor are there any that are being designed. The first task in the development of such a system is to prove the concept. Once the concept is deemed viable, careful design of an electro-optical device will be needed for the successful integration of low light visible, imaging infrared and spectral infrared sensors in the many applications that can utilize the sophistication of these systems.

6.2 Experimentation Needed for the Proof of Concept

Proof of concept experimentation should center around three themes.

The first group of experimentation should be designed to discover the amount of information that can be extracted from stack effluents. High resolution (0.01 wave number) spectroscopy of a stack effluent source should be conducted. The goal will be to

identify the spectral lines that are most prominent as well as those of the trace constituents. Analysis should include the rotational and vibrational identification of all lines present. Estimates of their intensities are required so that subsequent design efforts will be able to correctly select the bands and band widths to meet the required application. After the available information is identified, fuel type and engine operating parameters should be varied to determine information about the ratios of lines.

The second theme around which to design experimentation should discover the ranges at which these systems will be reliable and the bandwidth of the filters that will be required. Once several candidates are selected for spectral analysis, the range and bandwidth needs to be varied. The results should be correlated so that the maximum range of detection can be found.

The third theme around which to design experiments will be to identify the correct band(s) and bandwidth(s) that will give the best real time analysis of the background radiance. Experiments should be done to record the background radiance. The band(s) that most reliably correlates to the radiance of the atmosphere during all conditions of the marine environment are the correct choice.

6.2 Application in a Submarine Periscope

The engineering of an infrared device for installation onboard a submarine will provide a true challenge. The first order of business in submarine design is space. All of the optics, filters, detectors, coolers and pre-amplification devices required by the not only the spectral system but those required for any visible system or infrared imaging system must be contained in the periscope barrel. The number of periscope barrels is limited to two. A certain amount of redundancy must be engineered into the two barrels so that the submarine will never be "blind".

Added to the above physical requirements are the need to ensure that the designed system is reliable and maintainable. Maintenance of the detector elements at depot or intermediate levels will be beyond the ability of those organizations and therefore replaceable detector pods will be required. These plug-in and bolt-on pods will contain as a minimum the optics, detector elements and the source of cooling. If the system is designed to be "staring", the number of moving parts will be minimized and hence the reliability of the system will be greatly enhanced.

The ideal employment of a infrared spectral detection system that is supported by the technology at hand is as a threat warning system. It would be

designed as a staring system that would operate in conjunction with a day/high visibility periscope and a night/poor visibility periscope. Its intended purpose should be to provide the operator with real time threat analysis as the scope is raised. Future design considerations would be to start to use the information that is available from the detection of trace constituents and the ratios of lines. What ever design is selected or proposed, it must be within the tactical doctrine of the U. S. Submarine Force to ensure covertness of the ship and success in the deployment detector.

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